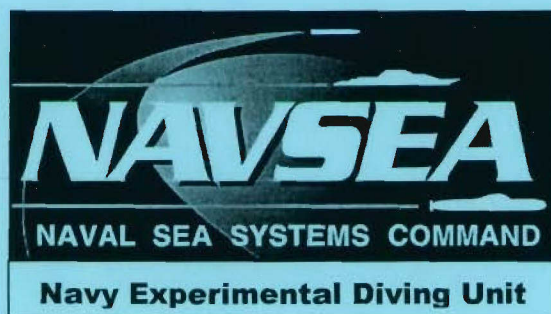


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MULTISPECIES DECOMPRESSION MODEL USING ASYMMETRICAL GAS KINETICS



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ABSTRACT

This project developed and evaluated a new mathematical decompression model with asymmetrical gas kinetics. The intended application was to support U.S. Navy diving operations involving surface decompression with oxygen (O_2) following air diving (Sur-D O_2). Before this effort, the most sophisticated model for predicting human risk of decompression sickness (DCS) following exposure to elevated O_2 mixtures was one developed in 1998 and based on only a small amount of Sur-D O_2 data. The present effort added more than 4,000 dives, particularly dives with high O_2 and/or Sur-D O_2 , to the data for calibration of the new model. About half of the added dives were experimental exposures involving rats, in the hope that higher-risk animal dives would improve prediction accuracy for higher-risk human dives. It was also thought that sharing parameters between the species, particularly those parameters defining the effect of O_2 on decompression risk, might enhance model performance. However, we were unable to demonstrate an advantage of the rat-human model over the human-only or the 1998 models. We used all three models to evaluate three possible alternative Sur-D O_2 procedures, each alternative having more flexibility than those currently in use but varying in amounts of DCS risk. The Navy can now evaluate changes in Sur-D O_2 procedures by using all three models. When new procedures are considered for Fleet use, this approach may enhance decision making without requiring a manned dive trial.

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INTRODUCTION

Recent experience shows that the Navy still lacks the ability to effectively employ O₂ as a decompression tool. This is evident by:

1. perceived high decompression sickness (DCS) incidence using surface decompression procedures with O₂ following air diving (Sur-D O₂) during the recovery of TWA flight 800,¹ and
2. NAVSEA's acknowledged continued desire to improve the use of O₂ in order to optimize decompression schedules (*balance in-water vs total decompression time depending upon objective, etc*).

In order to evaluate changes to decompression tables, tools are needed that can predict DCS outcomes based upon the decompression schedule. For the past two decades, probabilistic models have been developed for this purpose.^{2,3} Until now, the most sophisticated probabilistic model used to evaluate procedures using elevated partial pressures of O₂ (including Sur-D O₂) was based on only a small amount of Sur-D O₂ data.³ A new probabilistic model was developed in present work and used to predict human DCS risk following exposure to elevated O₂ mixtures. The three notable aspects of this model are

1. time constant asymmetry between uptake and washout,
2. an expanded human nitrox data set, and
3. the use of animal data to expand depth/time/PO₂ scope of calibration data beyond that of the human data.

METHODS

MODELS

We used a class of models that incorporate asymmetrical gas kinetics and that this report refers to as "ASYM." Based on standard exponential kinetics for the gases, the ASYM model was the basis of earlier work with human⁴ and human/rat decompression models.⁵ The asymmetry has been used previously in a deterministic model⁴, but this is a first attempt to estimate the parameters in a probabilistic context. We chose this model over the Linear-Exponential (LE) models of previous work due to its flexibility in allowing gas elimination to be either faster or slower than uptake, which was not possible for the LE models.

Our models were constructed with a series of theoretical gas-exchange "compartments" or "tissues" which, for modeling purposes, were independent, parallel-perfused compartments. The number of these compartments affects how well the model fits the data. The novel feature of ASYM is that the time constant governing blood-tissue gas exchange kinetics for compartment j assumes one of two possible values depending on the calculated tissue inert gas overpressure in that compartment:

$$\tau_{i,j} = \tau_{i,j}; \quad \sum_i P_{i,j} \leq P_{amb} + P_{thr_j} \quad (1a)$$

$$\tau_{i,j} = \tau_{i,j} \cdot asym_j; \quad \sum_i P_{i,j} > P_{amb} + P_{thr_j} \quad (1b)$$

Here tau (τ) is the compartment (j) time constant of gas ' i ', P_i is the partial pressures of the inspired gas ' i ', P_{amb} is the ambient pressure, P_{thr} is the estimated threshold parameter, and *asym* is the asymmetry parameter affecting the rate of gas washout. The modified time constants due to the *asym* parameter are active during decompression; thus, this parameter can be thought of as either slowing down (*asym* > 1) or speeding up (*asym* < 1) gas washout during this phase of a dive. With *asym* = 1, gas uptake and washout are equal.

This project was aimed at decompressions using high levels of O₂, so an explicit contribution by O₂ to DCS risk was incorporated into the model. This was done in a manner similar to that of Parker et al.³ for human diving in their model #2. That model, which will be referred to as "JAP98," defined the role of O₂ as adding to the inert gas load by contributing to bubble formation and/or growth when the inspired O₂ partial pressure is greater than parameter P_{set} . Thus, the portion of the ambient partial pressure of O₂ that exceeds the P_{set} value is treated as an inert gas. In our model, the gas exchange between the ambient environment and the tissue was governed by blood perfusion limitations according to the equation

$$\frac{dP_{i,j}}{dt} = \frac{P_{amb_i} - P_{i,j}}{\tau_{i,j}}, \quad (2)$$

where P_i is the partial pressure of gas i dissolved in the tissue, P_{amb_i} is the partial pressure of gas i in the inspired gas, and τ_i is the time constant for gas i , all in compartment j . For the case of O₂, the P_{amb_i} is replaced by $(P_{amb_{O_2}} - P_{set})$, with this term constrained to be greater than zero:

$$\frac{dP_{O_2,j}}{dt} = \frac{(P_{amb_{O_2}} - P_{set,j}) - P_{O_2,j}}{\tau_{O_2,j}} \quad (3)$$

To evaluate the ASYM model, we needed to define risk. The instantaneous risk for a given compartment was defined to be the supersaturation above a threshold (P_{thr}):

$$risk = \sum_j^{comp} gain_j \cdot \left(\sum_i P_{i,j} - P_{thr_j} \right), \quad (4)$$

where *gain* is a scale factor and j is the index of the individual compartments. The probability of no-DCS in the 0 – T interval is then

$$P(noDCS) = e^{-\int_0^{T_1} risk \bullet dt}, \quad (5)$$

where integration of the risk occurs until risk falls to zero. We included the onset time of DCS in our models, as experience suggests that including this time improves estimates of model parameters.⁶ Similarly, the probability of DCS occurring within a time interval between times T_1 and T_2 is defined as

$$P(DCS) = e^{-\int_0^{T_1} risk \bullet dt} \bullet \left(1 - e^{-\int_{T_1}^{T_2} risk \bullet dt} \right), \quad (6)$$

where T_1 is the last time the individual was known to be symptom free and T_2 is the first time that symptoms are sufficient to make a diagnosis.⁶

Once we have defined the probability of an event occurring, we can use the method of maximum likelihood to match this to the outcomes for these profiles, which assumes independent events. The likelihood (L) is the joint probability of observed outcomes given the model⁷:

$$L = \prod_n^N P(DCS_n)^{\psi_n} \bullet P(noDCS_n)^{1-\psi_n}, \quad (7)$$

which is the product of probabilities for each dive profile, n , over all the dive profiles, N , where $\psi_n = 1$ if DCS, or $\psi_n = 0$ if no DCS. As L becomes a small number when multiple dives are considered, we used the log-likelihood (LL), which is the natural logarithm of the above expression. The best match between a model and the outcomes in the data occurs when the likelihood is maximized. We used parameter estimation techniques to modify the model parameters to find this maximum value, which is our “best fit.”

DATA

Human

A total of 6,207 human nitrox exposures were used for (Table 1), nearly 2,000 more than in any prior published analysis. These additional exposures included a number involving high inspired partial pressures of O_2 that have never been included in a calibration data set for a probabilistic model. Specifically, the data set consisted of

1. the 26 data sets used with a previously reported human model that included O_2 in the prediction of DCS,³ (this information is shown on Table 1, [3]), and
2. an additional 12 data subsets from earlier research efforts.⁸

Table 1. Human data sets used for modeling^[1].

Data Set	Depth (fsw)	Bottom Time (min)	Number of Exposures	Observed Cases of DCS ^[2]
Single Air				
EDU885A ^[3]	50 – 190	14 – 244	483	30
UPS290	60 – 625	0 – 5	299	4
DC4W ^[3]	49 – 265	9 – 100	244	8.4
EDU849LT2 ^[4]	100 – 150	27 – 60	73	9.2
NMR97NOD	100 – 170	38 – 85	103	3.4
NMRNSW ^[3]	61.5	82 – 364	91	5.5
PASA ^[3]	101 – 151	30 – 62	72	5.2
SUBX87 ^[3]	80 – 602	0 – 2	58	2
Single Non-Air				
NMR8697 ^[3]	25 – 130	30 – 240	477	12.8
EDU1180S ^[3]	75 – 150	38 – 126	120	10
EDU885M ^[3]	100 – 150	44 – 66	81	4
Repetitive and Multilevel Air				
PAMLA ^[3]	51 – 82	61 – 452	236	14.2
EDU885AR ^[3]	80 – 150	29 – 62	182	11
PARA ^[3]	61 – 152	25 – 70	135	7.3
DC4WR ^[3]	120 – 180	30 – 40	12	3
Repetitive and Multilevel Non-Air				
EDU184 ^[3]	40 – 150	23 – 366	239	11
PAMLOAS ^[3]	61 – 82	33 – 637	140	5.3
PAMLAOD ^[3]	61 – 82	241 – 540	134	6
EDU885S ^[3]	60 – 150	43 – 124	94	4
Air with Oxygen Decompression				
NMR94EOD ^[3]	60 – 170	40 – 240	284	17.9
DC8AOD ^[3]	59 – 300	2 – 60	256	3.2
DC8AOW ^[3]	90 – 180	2 – 208	46	3.1

^[1] Listed by original data set names

^[2] Observed cases = diagnosed cases + 0.1 • marginal cases

^[3] Data sets to which model JAP98 was fit, as described in Parker et al., 1998 (reference 3).

^[4] Only the resting dives were used from this study.

Table 1. Human data sets used for modeling (continued).

Data Set	Depth (fsw)	Bottom Time (min)	Number of Exposures	Observed Cases of DCS ^[2]
Saturation				
ASATNSM ^[3]	25 – 132	2880 – 11760	132	20.1
ASATEDU ^[3]	50 – 60	740 – 2884	120	15.7
SUREX	65 – 75	5460 – 7020	24	5.3
ASATNMR ^[3]	20 – 24	4320 – 6181	50	1
NMR9209	20 – 22	4284 – 4399	48	2.5
EDUAS45	33 – 99	360 – 2160	26	5.6
ASATDC	26 – 33	1440 – 1454	23	8.1
ASATARE ^[3]	23 – 78	2862 – 2895	165	21.3
Subsaturation				
EDU849S2 ^[4]	33 – 40	720	30	5.8
NSM6HR ^[3]	28 – 40	359 – 360	57	3.2
Surface Decompression on Air				
EDU545SUR ^[4]	100 – 170	30 – 85	102	10.3
NMRASUR90	60 – 120	49 – 180	64	0
Surface Decompression on Oxygen				
EDU1351SD ^[5]	74 – 214	20 – 130	1035	43.3
DC8ASUR ^[3]	59 – 236	30 – 70	358	10.1
DCSUREP ^[3]	147 – 172	30 – 230	69	1
NMROSUR90	60 – 120	49 – 179	45	1

^[3] Data sets to which model JAP98 was fit, as described in Parker et al., 1998 (reference 3).

^[4] Only the resting dives were used from this study.

^[5] Sur-D O₂ was assumed to have inspired O₂ fraction of 90%.

For previous efforts, we had established a strict set of requirements⁹ for acceptance of calibration data. One of these requirements was that we reconcile data questions with the author/principal investigator of the study that generated the original data set. However, the historical data was too old for such reconciliation. Therefore, we decided to relax this specific criterion. We were confident that the depth-time-gas mix histories could be reconstructed, but were less certain about addressing questions on DCS outcomes. The severity of the historic dive profiles resulted in high DCS incidences¹⁷ that would probably be even higher than recorded if today's more conservative diagnostic criteria had been used. Fortunately the postdive descriptions of DCS signs and symptoms were available, so a panel of DMOs could (and did) rediagnose all outcomes with a standard set of criteria.^{8,9}

The human data showed an average DCS incidence of 4.8% (11.2% when marginal cases were included as full cases), with a depth range of 20 to 625 fsw (maximum of 297 fsw when submarine escape dives are excluded), and an O₂ partial pressure range

of 0.3 to 4.2 ata (max 2.7 ata with the exclusion of the submarine escape dives, which are characterized by very short duration to great depths, with rapid ascents).

Rat

A total of 2,390 rat dives used for the animal component included many dives with elevated O₂:

1. 2,120 nitrox dives over a large range in pressures, bottom times, decompression profiles, and O₂ pressures, and
2. 270 dives from an experiment that involved switching the inspired partial pressure of O₂ at depth before decompression.

The 2,120 nitrox dives had a DCS incidence of 50.5%, with a depth range of 141–275 fsw and oxygen partial pressures up to 3 ata. The 270 oxygen switching dives had a 61.1% incidence of DCS, with a depth range of 225 to 275 fsw. These dives were conducted for 60 min on air, with 135 control animals continuing on air, while the others switched to 42% nitrox before decompression.

The 2,120 nitrox dives have been described previously.¹⁰⁻¹⁴ The 270 O₂ switching dives were conducted in a similar fashion.

Time of DCS

The 12 new human data sets were found to contain inconsistencies in the times related to onset of DCS. To correct this problem, we chose a conservative approach for standardizing the T₁ and T₂ values for the human dives. The T₁ values were set to an earlier time than recorded: either the closest documented medical check time or the end of the bottom time, whichever was later. The T₂ times were moved to a later time than recorded, which was the next documented medical check time. As our rat data contained only the time at which DCS was first observed during the experiment, we needed to establish rules for defining T₁ and T₂ times for these dives. As with the human data, we were conservative with the rat data: we defined T₁ for rats as the time leaving the bottom and T₂ as the original time when DCS had been observed.

These modifications reduced the effect of the additional dives on the estimated parameters in the model, as they made the times less precise. However, without evaluating and setting the T times according to a fixed and consistent set of rules with the full rigor that was used for the previous data sets, we felt that it was necessary to err on the side of caution.

PARAMETER ESTIMATION

Model parameter values were adjusted to maximize the model log likelihood (LL) about the calibration data using a modified Marquardt nonlinear estimation algorithm.¹⁵ This fitting process required defining the starting values of all parameters. However, for such complex models as these, we had to perform the fitting process repeatedly with many possible combinations of starting parameter values to improve the chances of finding a global maximum in the likelihood surface (i.e., best fit). To facilitate the fitting process, we created a tool that generated multiple sets of starting parameter values randomly selected from a user-defined range. This tool helped us perform a quasi-global search of the parameter space with the starting parameter values limited to plausible areas. Once we obtained a possible maximum in the likelihood surface, we had to test whether it was truly a global or a merely a local maximum. This was done by modifying the last best-fit parameter values by randomly adding or subtracting varying amounts to create new starting parameter value sets, which were then used to conduct confirmation searches for other maxima. If none were found, we broadened our search until we felt confident that the best fit was obtained. More than 500 runs were completed to confirm each of the final parameter sets reported.

For the combined species model, each rat parameter was set equal to the corresponding human parameter plus a delta parameter. For example, the rat asym parameter was given by:

$$asym_{rat} = asym_{human} + \Delta asym_{rat} \quad (8)$$

where the possible estimated parameters were $asym_{human}$ and $\Delta asym_{rat}$. In order to link the species in the combined species model, we defined several of the parameters as common (i.e., set equal) between humans and rats by fixing the delta parameter at zero. This minimized the number of estimated parameters, and provided a means by which the rat data could affect model fit to the human data. These shared parameters were

1. $asym$, the asymmetry parameter which affects the mathematical relationship between gas washout and gas uptake, and
2. P_{set} , which defines the pressure at which O_2 begins to contribute to risk.

The parameters for which the deltas were estimated were:

1. τ , time constants for N_2 and O_2 ,
2. P_{thr} , the threshold pressure above which risk accumulates, and
3. $gain$, the scale factor for each compartment.

Estimation of these deltas effectively made these parameters species-specific.

The likelihood ratio (LR) test was used to evaluate the significance of estimated parameters on the basis of improvement in fit.⁷ As parameters were added to the model, they were tested for significant improvement, by calculating the LR statistic

$$LR = 2 \cdot [LL_{additional} - LL_{base}], \quad (9)$$

where LL_{base} is the LL of the model prior to the parameter additions, and $LL_{additional}$ and is the LL of the same model with the additional parameters being estimated. This setup creates a nesting relationship for the models, making one a subset of the other. This allows us to look up the LR statistic on the Chi-squared tables (with the number of additional parameters being the degrees of freedom) to assess if the addition is statistically significant at a given confidence level (we use 95%). In our case, all of the parameters exist in the model code at the start, but had their values fixed to remove any contribution to the model risk (thresholds fixed at zero; P_{set} s fixed at 99).

As a final step in the addition of parameters, we tested the addition of delta *asym* and P_{set} parameters for rats, which effectively separated the species by allowing all possible parameters to have independent values. The LR test of the addition of these two parameters is effectively also a test that determines whether the human and rat data sets were statistically combinable:

$$LR = 2 \cdot [LL_{independent} - LL_{combined}], \quad (10)$$

where $LL_{combined}$ is the LL of the described combined model fitted to the combined data sets, and $LL_{independent}$ and is the LL of the same model with remaining delta parameters estimated, which effectively made the human and rat expressions independent. Data sets not combinable by this criterion generally produce better predictions of decompression risk when modeled separately. However, past work, with different types of human dive trials, has succeeded while ignoring this fault.⁹

RESULTS

MODEL PARAMETERS

Model parameters estimated for the human-only and combined human/rat data are presented in Tables 2 and 4. Only parameters found to be significant at $P \leq 0.05$ by the LR test are reported. Parameter significance was determined by building on the basic model (with minimal parameters), adding one or two parameters at a time, and then using the appropriate number of degrees of freedom (one per parameter added) to apply the LR test. The O_2 parameters (P_{set} and τ) were added to determine how significant any O_2 effect would be, as demonstrated by a significant increase in LL . Because of the sequential nature of the model fitting process, the true confidence level of both the parameters and the final model should be less than what might be expected. In some cases, parameters were fixed at specific values rather than estimated, and these parameters are noted by having no standard error.

The best-fit human-only model (Table 2) had three compartments with no asymmetry and a significant O₂ effect only in compartment 1, with 10 significant estimated parameters out of a possible 18. The human-only model is a presentation of just the human parameters of the independent model, as it is equivalent to fitting just the human parameters to the human-only data, for the purposes of making risk predictions on human exposures. Because the estimated value for P_{set} was small in compartment 1 with a large confidence interval, it was fixed to zero. Fixing the P_{set} value improved the ability to estimate the other parameter values and effectively had us estimating 11 parameters. This effectively treated O₂ in a fashion similar to N₂ in the definition of DCS risk for that compartment. To remove the influence of O₂, P_{set} was fixed at 99.0 in the other two compartments, because the O₂ effect was not found to be significant. This finding, in turn, made the O₂ time constants meaningless, and values in these compartments are therefore denoted as N/A. Having similar values for the N₂ time constants for compartment 2 and 3, with rather large errors that allow the parameter ranges to overlap, was disconcerting. However, the thresholds for these two compartments were very different and standard errors on the thresholds were tight. This parameter set was confirmed by more than 1,000 additional model fits.

Table 2. Human-only ASYM model: Parameter values \pm standard errors.

Parameter	Compartment 1	Compartment 2	Compartment 3
N ₂ Time Constant (min) τ_{N_2}	3.8 ± 0.5	330 ± 20	390 ± 70
O ₂ Time Constant (min) τ_{O_2}	1.4 ± 0.2	N/A	N/A
<i>asym</i>	1.0*	1.0*	1.0*
Natural Logarithm of the Gain	-5.4 ± 0.4	-7.5 ± 0.1	-4.7 ± 0.3
P _{thr} (atm)	0.7 ± 0.2	0.07 ± 0.01	0.51 ± 0.04
P _{set} (atm)	0.0*	99.0*	99.0*

* Fixed

The human and rat data sets failed the test for combinability, as evidenced by the very significant increase in LL (+ 17.1) with the addition of 5 parameters (2 Δ P_{set}s, 3 Δ asym)s) when the model made the predictions for the 2 species independent of the calibration data for the other species (Table 3). However, our experience has shown that it is often difficult to pass the LR test when assessing the combination of human data sets. Given that one of the primary goals of this project was to produce and evaluate a multispecies model, we proceeded with the combined human/rat model.

Table 3. Log Likelihood values for the combined and independent species ASYM models.

Data	Log Likelihood (LL)	Number of Parameters
Combined	-2875.7*	27
Independent	-2858.6	32
Human	-1538.4	11

*, Significantly different ($P < 0.01$) from separate species models

The best-fit human/rat model (Table 4) was a 3-compartment model with asymmetry in all compartments and an O_2 effect in compartments 1 and 2. Using the likelihood ratio test, we found 27 of the 36 possible parameters in the combined model to be statistically significant. The observed asymmetry with faster washout than uptake is a phenomenon observed previously in rats.¹⁴ For this combined model, the *asym* and P_{set} parameters were forced to be the same for both the rat and the human compartments.

Table 4. Combined human/rat ASYM model: Parameter values \pm standard errors.

Parameter	Compartment 1		Compartment 2		Compartment 3	
	Human	Rat	Human	Rat	Human	Rat
N_2 Time Constant (min) τ_{N_2}	4.8 ± 1.1	0.6 ± 0.1	360 ± 30	0.4 ± 0.1	620 ± 80	10.6 ± 0.3
O_2 Time Constant (min) τ_{O_2}	2.4 ± 1.5	80 ± 10	0.9 ± 0.4	4 ± 2	N/A	N/A
<i>asym</i>	0.39 ± 0.07	Human**	0.82 ± 0.07	Human**	0.32 ± 0.04	Human**
Natural Logarithm of the gain	-4.7 ± 0.4	0.5 ± 0.3	-7.4 ± 0.1	2.7 ± 0.3	-4.4 ± 0.3	-0.5 ± 0.2
P_{thr} (atm)	0.4 ± 0.2	1.8 ± 0.2	0.05 ± 0.01	0.4 ± 1.1	0.44 ± 0.03	2.9 ± 0.1
P_{set} (atm)	0.2 ± 0.1	Human**	1.1 ± 0.2	Human**	99.0*	Human**

* Fixed

** Fixed equal to the human value.

The values of the human parameters for the models fitted to the human-only and combined data were different, but the predictions for the human data sets reported in reference 8 were not greatly affected (see Appendix A). Thus, including the higher-risk rat dives in the calibration data did not improve the ability to predict human dives. That the human-only model did not include asymmetry but predicted comparably to the combined species model indicates that the human data was described equally well with or without asymmetry.

PREDICTED DCS RISKS OF PRESENT AIR AND SUR-D O₂ TABLES

The predicted risk of DCS was not observed to be constant over the entire set of present Air and Sur-D O₂ tables, with risk as low as 2% for short dives and > 5% for longer dives (see Appendix B). We note, however, that the model predictions for any schedule are for the worst case — for the maximum time/depth — as we cannot foresee the actual depths and times that will be used. Differences in risk predictions between in-water and surface decompression schedules were inconsistent, although some of the inconsistencies may have resulted from the different techniques used to develop the two sets of tables (reference 16 (in-water) and reference 17 (Sur-D O₂)).

DISCUSSION

With an emphasis on dives with high O₂ and/or Sur-D O₂, this effort added over 4,000 additional dives for estimating the new model. About half of these added dives were experimental exposures involving rats, in the hope that the higher-risk animal dives would improve prediction accuracy for higher-risk human dives. We also thought that sharing of parameters between the species, particularly those parameters defining the effect of oxygen on decompression risk, might enhance model performance. Unfortunately, we were unable to demonstrate any significant advantage of the multispecies model over the human-only or the previously reported JAP98 model.³

It is interesting to note that in the combined human/rat model, the asymmetry parameters are < 1 for all three compartments indicating that modeled gas exchange is faster for washout than for washin. This result is the opposite from that previously reported for linear/exponential-based models using a subset of the present human data (see Table 1, JAP98). Those models displayed slower off-gassing characteristics by using bubble-like dynamics.⁴ However, there is some experimental¹⁸ and theoretical¹⁹ basis for faster elimination. This effect is driven by the rat data, as the human only model did not support asymmetrical gas kinetics (See Table 3).

We did not recalibrate the JAP98 model with the expanded human data set. However, both the JAP98 and ASYM models agreed well when comparing the model predictions and observed outcomes for previous data sets as seen in Table 5. Some data sets were better described by JAP98; others by ASYM. No consistent pattern was discernible. It should be noted, that while the older data (EDU557, EDU1351SD) was rediagnosed with a standard set of criteria, it is highly likely that symptoms of DCS that would be treated today (under present criteria), would not have been noted at the time;

thus the observed incidences for these data sets are expected to be low compared to the models predictions. A complete comparison of the data sets documented in reference 8 appears in Appendix A.

Table 5. Predicted DCS risks for previous data sets.

Dive Trial	# Dives	# DCS	#DCS Predicted by Model (95% Confidence Interval)		
			JAP98	ASYM Human/Rat	ASYM Human-only
1957 Standard Air (EDU557)	568	27	36 (29 - 43)	26 (22 - 30)	28 (23 - 32)
1951 Sur-D O ₂ (EDU1351SD)	1035	43	66 (49 - 82)	52 (30 - 73)	55 (49 - 60)
1983 Canadian Air Sur-D O ₂ (DC8ASURW)	98	5	2.4 (1 - 3)	2.5 (2 - 3)	2.6 (2 - 3)

With input from NAVSEA 00C and the Fleet, we evaluated the DCS risk associated with possible changes to the present Sur-D O₂ decompression tables. Because no single model appeared "best," we used both the ASYM and JAP98 models to evaluate three possible alternative Sur-D O₂ procedures, each having more flexibility than current procedures but varying in its amount of DCS risk. (We have been told that until the final pull to the surface for chamber decompression, the flexibility of having Sur-D O₂ schedules match the in-water air schedules for the same range of depths and bottom times would benefit dive supervisors.) As the calibration data has been expanded with this modeling effort, we expected the risk predictions from the ASYM models to differ from the predictions using JAP98. However, we gained added confidence when and where there was agreement between the models.

As a first step, we wanted to evaluate how risky current Sur-D O₂ procedures are. The first dive we considered was to 120 fsw for 60 min, followed by decompression using the current 120/60 schedule (Table 6). The Fleet (i.e., U.S. Navy master divers) indicated that this dive profile was uncomfortably risky and is not routinely used. As illustrated in Table 6, the predicted risk ranges from 5% to 7%, which agrees with the Fleet's perception of high risk. The second dive, to 112 fsw for 52 min, demonstrates the range of risk possible due to the step sizes (time and depth) of the current Sur-D O₂ Table; this range demonstrates that the risk can be changed by > 2 % while diving a correctly chosen schedule. The third dive "jumps" to the 120 fsw for 90 min schedule, a dive that was reportedly made during the TWA 800 recovery operation and that cuts the risk by about one-third. With regard to these models, the 2.5% to 3% risk of this schedule might be viewed as an estimate of the degree of risk acceptable to the Fleet.

Table 6. Predicted DCS risks of surface decompression schedules.

Dives (fsw/min), Decompression Schedule	Risk Predicted by Model (%) (95% Confidence Interval)		
	JAP98	ASYM Human/Rat	ASYM Human-only
120 / 60 on 120 / 60 Sur-D O ₂ Schedule	7.0 (5.8 – 8.1)	4.8 (4.0 – 5.5)	5.2 (4.5 – 5.9)
112 / 52 on 120 / 60 Sur-D O ₂ Schedule	4.7 (3.8 – 5.7)	3.7 (3.0 – 4.3)	4.0 (3.4 – 4.5)
112 / 52 on 120 / 90 Sur-D O ₂ Schedule	3.2 (2.2 – 4.2)	2.6 (1.9 – 3.3)	2.5 (1.9 – 3.0)

We next wanted to examine how these models behaved with respect to different types of dive profiles before we proceeded to possible new Sur-D O₂ options. Unfortunately, the use and evaluation of probabilistic decompression models can quickly produce a collection of numbers far too large to manage. Thus, we adopted a standard set of hypothetical profiles to characterize model performance (Table 7). Previous studies have shown some of the standard profiles included here to be particularly “safe” or particularly “dangerous.” We include brief descriptions of real dives similar to the hypothetical profiles to assess the models.

The first two profiles in Table 7 are for submarine escape profiles. Use of the British SEIE equipment has been uneventful in many exposures to 400 fsw and shallower. However, deeper trials have produced some cases of DCS.^{20,21}

The 60/60 with “rapid” ascent is a common benchmark. Some people think that slowing the ascent to take an additional minute or two would significantly reduce DCS risk, but the value of this approach remains unsubstantiated. Many thought that an additional 20 min at 60 fsw would be devastating, but it did not appear so when actually performed.²²

The 60-min exposures to 49 and 80 fsw have the same nitrogen profile as 60 fsw on air, but the oxygen partial pressure varies, a procedure previously shown to have negligible effects.²³

The three saturation profiles span the range from no observed DCS (20 fsw) to a non-trivial observed incidence of DCS (30 fsw).

The initial 60 fsw for three hours schedule was problematic and required substantially more decompression time than required by the air tables to become acceptable.²⁴ The next several profiles represent alternate ways to decompress from the same exposure.

The final pair is surface decompression possibilities, one of which was found more satisfactory than another.¹

From Table 7 we conclude that the estimates are not fully consistent with experience (See Appendix F for confidence intervals). As with the prior model USN93,²⁵ all three models overestimate the risk from a 20 fsw saturation dive. Overestimation probably occurs for the shortest dives as well as for rapid submarine escapes. Within the middle time range, it appears that ~ 3% is "safe" by JAP98, while $\geq 6\%$ is probably "unsafe". The two ASYM models behave similarly: they also seem to have ~ 3% as "safe" and $> 6\%$ as "unsafe." Other benchmarks can be used based upon the predictions for schedules that are familiar (Appendix B).

Table 7. Standard profiles with predictions from the three models.

Profile Description (All air dives, unless noted)	Risk Predicted by Model (%)		
	JAP98	ASYM Human/R at	ASYM Human-only
Submarine escape from 400 fsw in SEIE	5.0	8.2	8.6
Submarine escape from 600 fsw in SEIE (2.7 min)	10.1	13.1	14.3
60 fsw for 60 min ascent 60 fsw/min	2.2	2.5	2.3
60 fsw for 60 min ascent 20 fsw/min	2.1	2.2	2.1
60 fsw for 80 min ascent 60 fsw/min	3.3	3.5	3.3
60 fsw for 80 min ascent 20 fsw/min	3.2	3.1	3.1
49 fsw for 60 min on 10% Oxygen (60/60 equiv)	2.3	2.4	2.2
80 fsw for 60 min on 35% Oxygen (60/60 equiv)	2.2	2.8	2.5
20 fsw saturation ascent 60 fsw/min	6.8	5.8	5.1
25 fsw saturation ascent 60 fsw/min	10.9	12.3	9.2
30 fsw saturation ascent 60 fsw/min	15.2	21.9	19.0
60 fsw for 180 min by USN in-water schedule	9.3	6.9	7.0
60 fsw for 180 min by USN93 schedule	6.4	5.7	5.9
60 fsw for 180 min with 14 min O ₂ at 20 fsw	8.0	6.6	6.7
60 fsw for 180 min with 14 min O ₂ during ascent	8.0	6.5	6.7
60 fsw for 180 min by USN Sur-D O ₂ schedule — 1 min SI	5.6	5.5	5.4
60 fsw for 180 min by USN Sur-D O ₂ schedule — 3.5 min SI	5.7	5.5	5.5
60 fsw for 180 min by USN Sur-D O ₂ schedule — 6 min SI	5.7	5.5	5.6
60 fsw for 180 min — 1 hour Oxygen at 20ft	2.5	4.2	4.2
TWA 800 — 116/85 on the 120 for 90 Sur-D O ₂ schedule	6.7	5.3	5.5
TWA 800 — 116/59 on the 120 for 90 Sur-D O ₂ schedule	3.2	3.2	3.2

We have no reason to believe that one of these models is better than the others. We proceeded with all 3 models, knowing that if the predictions diverged, we were extrapolating beyond the applicable depth time range of at least one of the models, we would then need additional tools.

We then began to use the three models to predict the risk of possible changes to current U.S. Navy Sur-D O₂ procedures. One of the issues we wished to address was the apparent need by U.S. Navy divers to jump Sur-D O₂ decompression schedules (e.g., to use a 120/90 decompression schedule following a 120/60 dive)¹. At the same time, we wanted to add the flexibility of having Sur-D O₂ schedules match the air schedule until the final pull to the surface for chamber decompression, flexibility that will allow divers easily to switch from the Navy's standard air decompression to Sur-D O₂ without needing to decide before starting decompression, as they now must do. Lastly, we wanted to expand the procedures to cover the same depth and time ranges as those for in-water decompression. Currently, the Sur-D O₂ tables go only to a maximum depth of 170 fsw, while the air decompression tables continue to 190 fsw.

As a first step, we assessed the risks of schedules in both the present air decompression tables and the present Sur-D O₂ tables (Appendix B). We then examined three possible Sur-D initiation rules from standard air (STD AIR) schedules as demonstrations for selecting new surface decompression schedules. This approach may allow a decision about adopting a given procedure for Fleet use to be made without requiring a costly manned dive trial.

The three Sur-D initiation rules from STD AIR schedules we chose were the following:

- 1) 40/min5/half. Perform all the in-water decompression required by the air tables until the 40 fsw stop is reached. Then perform either a full or a five-minute stop time (whichever is greater), and pull to the surface. Return the diver to pressure in a chamber within five minutes, and perform decompression on O₂ at 40 fsw equivalent for half of the remaining decompression time (30, 20, and 10 fsw stops). Air breaks are to be used, but these times do not count toward the O₂ decompression time.
- 2) 30/min5/half. Perform all the in-water decompression required by the air tables until the 30 fsw stop is reached. Then perform either a full or a five-minute stop time (whichever is greater), and pull to the surface. Return the diver to pressure in a chamber within five minutes, and perform decompression on O₂ at 40 fsw equivalent for half of the remaining decompression time (20 and 10 fsw stops). Air breaks are to be used, but these times do not count toward the O₂ decompression time.
- 3) 40/min5/three-quarters. Perform all the in-water decompression required by the air tables until the 40 fsw stop is reached. Then perform either a full or a five-minute stop time (whichever is greater), and pull to the surface. Return the diver to pressure in a chamber within five minutes, and perform decompression on O₂ at 40 fsw equivalent for three-quarters of the remaining

decompression time (30, 20, and 10 fsw stops). Air breaks are to be used, but these times do not count toward the O₂ decompression time.

The criteria to be compared among these options and the present Sur-D O₂ procedures include predicted risk of DCS and total decompression time (TDT). Other factors that may be important are the total in-water decompression time and the amount of time spent on oxygen because of concerns about oxygen toxicity. The amount of in-water time will depend on the depth of the last in-water stop. The risk of oxygen toxicity will be assessed after a procedure has been chosen; this risk can be minimized by using air breaks during the chamber decompression.

Table 8. Risk comparison of surface decompression schedules.

Dives (fsw/min), Decompression Schedule	Risk Predicted by Model (%) (95% Confidence Interval)		
	JAP98	ASYM Human/Rat	ASYM Human-only
120 / 60 on 120 / 60 Sur-D O ₂ Schedule	7.0 (5.8 – 8.1)	4.8 (4.0 – 5.5)	5.2 (4.5 – 5.9)
112 / 52 on 120 / 60 Sur-D O ₂ Schedule	4.7 (3.8 – 5.7)	3.7 (3.0 – 4.3)	4.0 (3.4 – 4.5)
112 / 52 on 120 / 90 Sur-D O ₂ Schedule	3.2 (2.2 – 4.2)	2.6 (1.9 – 3.3)	2.5 (1.9 – 3.0)
112 / 52 on Option 1: <u>40/min5/half</u>	4.6 (3.6 – 5.5)	3.4 (2.4 – 4.4)	3.4 (2.8 – 4.0)
112 / 52 on Option 2: <u>30/min5/half</u>	4.5 (3.5 – 5.5)	3.2 (2.1 – 4.3)	3.3 (2.7 – 3.9)
112 / 52 on Option 3: <u>40/min5/three-quarters</u>	3.5 (2.5 – 4.4)	3.0 (2.2 – 3.9)	3.0 (2.4 – 3.6)

All three of the Sur-D O₂ options we examined have smaller TDTs than those of the present air tables (which were deliberate choices; see Appendix C). However, option 3 (surface from 40 fsw, 3/4 of the remaining decompression time) is only slightly shorter than the present Sur-D O₂ schedules, with its advantages being shorter in-water time, and decreased risk of DCS (Appendices D and E). With a maximum predicted risk of 6.5%, this option has an appreciably lower maximum risk than those of the other two options and the present air or Sur-D O₂ tables: 9% for the present air, and 11% for the Sur-D O₂ tables. Thus, option 3 is the most conservative choice for risk of DCS. Options 1 and 2 have similar TDTs, with predicted risks slightly lower for option 2 (surface from 30 fsw) than option 1. The big difference between these two choices is in the amount of in-water decompression time. With both of these options, the TDTs are

up to 10% longer and the risks of DCS are slightly less than those of the present Sur-D O₂ procedures.

We can now examine these three new options in relation to the 112 fsw for 52 min profile (Table 8). In this case, we can see that all three options have predicted risks lower than the present schedule, but not as low as jumping to a 90-minute schedule. The first two options have very similar risk predictions, with their differences being in the amount of time spent in the water. Using the ASYM models, we can also see that the difference between the options is minimal, although the TDT varies from 42 to 60 minutes for these two options. This 18-minute difference in decompression, even while on oxygen, affects the predicted outcome of the dives only by < 0.5% based on the ASYM models; the difference is greater for JAP98.

Using the TDT information plus the risk predictions compared to the present air and Sur-D O₂ tables in Appendices D and E, an informed risk analysis decision can be made about the options we are presenting.

CONCLUSIONS

There was no improvement to the predictions of the ASYM model by using a data set combining rat and human data, over using the human data alone when calibrating the model.

The value of these models will be in their future use as additional risk prediction tools that help in determining when predictions are extrapolations.

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Appendix A

Predicted DCS Risks of Data Sets in Reference 8

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Predicted DCS Risks of Data Sets in Reference 8

Data Set	N	Observed	Predictions					
			JAP98		ASYM – H/R		ASYM – H	
			Predictions Confidence Limits		Predictions Confidence Limits		Predictions Confidence Limits	
Single Air								
DC4D	797	19.4	15.3	(11.5 – 19.1)	19.0	(14.9 – 23.1)	19.9	(16.3 – 23.5)
EDU557	568	27	35.8	(29.0 – 42.7)	26.4	(22.4 – 30.4)	27.5	(23.3 – 31.6)
EDU885A	483	30	26.5	(22.0 – 31.1)	22.9	(19.9 – 25.9)	23.4	(20.3 – 26.5)
UPS290	299	4	3.7	(–0.1 – 7.4)	3.8	(1.16 – 6.4)	4.5	(2.0 – 7.0)
DC4W	244	8.4	7.0	(5.6 – 8.4)	6.4	(4.8 – 8.0)	6.8	(5.4 – 8.2)
EDU1351NL	143	2.7	3.4	(2.61 – 4.3)	3.7	(3.0 – 4.4)	3.9	(3.5 – 4.3)
EDU849LT2	141	29.8	7.4	(5.6 – 9.2)	5.9	(5.0 – 6.8)	6.3	(5.5 – 7.1)
NMR97NOD	103	3.4	6.0	(4.9 – 7.2)	4.7	(4.0 – 5.5)	4.7	(4.0 – 5.5)
EDU545	94	18.7	7.4	(6.0 – 8.8)	5.0	(4.3 – 5.7)	5.1	(4.5 – 5.8)
NMRNSW2	91	5.5	6.8	(5.7 – 7.8)	5.2	(4.5 – 5.9)	5.2	(4.4 – 6.0)
PASA	72	5.2	3.6	(2.8 – 4.3)	3.1	(2.7 – 3.6)	3.1	(2.7 – 3.5)
SUBX87	58	2	0.6	(0.0 – 1.3)	0.4	(0.0 – 0.8)	0.4	(0.2 – 0.7)
EDU1157	46	15.6	13.4	(10.1 – 16.5)	11.5	(9.1 – 13.8)	17.8	(14.6 – 21.1)
Single Non Air								
NMR8697	477	12.8	16.4	(13.8 – 18.9)	17.1	(14.7 – 19.5)	16.4	(11.3 – 21.5)
EDU1180S	120	10	10.1	(8.5 – 11.7)	6.1	(5.3 – 7.0)	6.4	(5.5 – 7.4)
EDU885M	81	4	4.77	(3.9 – 5.6)	3.4	(2.9 – 3.9)	3.5	(3.0 – 4.0)
Repetitive and Multilevel Air								
PAMLA	236	14.2	21.0	(17.7 – 24.2)	16.2	(14.0 – 18.5)	17.0	(14.29 – 19.9)
EDU885AR	182	11	14.4	(11.8 – 16.9)	11.3	(9.6 – 13.0)	11.6	(9.9 – 13.3)
DC4DR	142	1	6.7	(5.3 – 8.1)	6.9	(5.8 – 8.0)	6.7	(6.1 – 7.4)
EDU657	142	4	10.3	(8.6 – 12.0)	8.4	(6.8 – 10.1)	8.6	(7.6 – 9.6)
PARA	135	7.3	11.6	(9.5 – 13.7)	10.4	(8.9 – 11.9)	10.4	(9.0 – 11.7)
DC4WR	12	3	1.2	(1.0 – 1.4)	0.8	(0.7 – 0.9)	0.8	(0.7 – 0.9)
Repetitive and Multilevel Non-Air								
EDU184	239	11	18.2	(15.2 – 21.2)	16.2	(13.8 – 18.6)	16.9	(14.6 – 19.2)
PAMLOAS	140	5.3	7.0	(5.7 – 8.2)	6.7	(5.8 – 7.7)	6.4	(5.4 – 7.3)
PAMLAOD	134	6	8.3	(6.4 – 10.2)	7.4	(6.3 – 8.4)	7.4	(6.3 – 8.5)
EDU1180R	128	2	14.2	(11.9 – 16.6)	10.7	(9.1 – 12.2)	12.5	(10.1 – 14.8)
EDU885S	94	4	5.5	(4.6 – 6.4)	4.6	(4.0 – 5.2)	4.6	(4.0 – 5.2)

Predicted DCS Risks of Data Sets in Reference 8 (Continued)

Data Set	N	Observed	Predictions					
			JAP98	ASYM – H/R		ASYM - H		
			Predictions Confidence Limits	Predictions Confidence Limits	Predictions Confidence Limits	Predictions Confidence Limits		
Air with Oxygen Decompression								
NMR94EOD	284	17.9	17.8	(14.1 – 21.5)	12.8	(10.4 – 15.3)	12.8	(10.4 – 15.2)
DC8AOD	256	3.2	6.6	(3.7 – 9.5)	6.2	(5.0 – 7.5)	6.7	(0 – 15.4)
DC8AOW	46	3.1	1.4	(0.9 – 1.9)	1.2	(0.9 – 1.5)	1.3	(1.1 – 1.5)
Saturation								
ASATARE	165	21.3	18.9	(14.8 – 23.1)	23.9	(18.9 – 28.8)	22.9	(17.9 – 27.9)
ASATNSM	132	20.1	22.6	(16.7 – 28.5)	19.4	(13.7 – 25.1)	19.9	(15.7 – 24.0)
ASATEDU	120	15.7	14.4	(10.8 - 18.0)	8.8	(5.3 – 12.3)	7.9	(6.0 – 9.7)
SUREX	24	5.3	4.4	(3.4 – 5.4)	9.2	(6.6 – 11.8)	7.3	(4.7 – 9.8)
ASATNMR	50	1	4.1	(3.3 – 5.0)	3.9	(3.1 – 4.8)	3.2	(2.5 – 3.8)
NMR9209	48	2.5	3.5	(2.7 – 4.2)	3.1	(2.3 – 3.9)	2.6	(2.1 – 3.0)
EDUAS45	26	5.6	5.5	(4.5 – 6.6)	8.5	(6.8 – 10.1)	9.2	(7.2 – 11.2)
ASATDC	23	8.1	3.0	(2.4 – 3.6)	3.6	(2.9 – 4.29)	3.7	(2.7 – 4.6)
AASATFR85	21	0	1.7	(1.4 – 2.1)	1.7	(1.3 – 2.1)	1.4	(0.9 – 1.8)
Subsaturation								
EDU849S2	60	14.7	9.0	(7.4 – 10.6)	10.0	(7.7 – 12.4)	14.4	(10.9 – 17.9)
NSM6HR	57	3.2	4.7	(3.9 – 5.6)	3.7	(3.2 – 4.3)	3.9	(3.0 – 4.8)
RNPLX50	57	5	7.3	(6.0 – 8.6)	7.7	(6.0 – 9.3)	10.6	(8.0 – 13.1)
Surface Decompression on Air								
EDU545SUR	197	28.2	16.2	(13.4 – 19.0)	11.4	(5.7 – 17.0)	11.5	(10.0 – 13.0)
NMRASUR90	64	0	4.7	(4.0 – 5.5)	4.0	(3.5 – 4.5)	4.1	(3.6 – 4.6)
Surface Decompression on Oxygen								
EDU1351SD	1035	43.3	66.1	(49.8 – 82.3)	51.8	(30.5 – 73.1)	54.8	(49.1 – 60.4)
DC8ASURW	98	5	2.4	(1.4 – 3.3)	2.5	(1.8 – 3.2)	2.6	(2.2 – 3.0)
DCSUREPW	17	1	0.6	(0.4 – 0.9)	0.8	(0.6 – 0.9)	0.8	(0.7 – 0.9)
NMROSUR90	45	1	1.9	(1.5 – 2.4)	1.8	(1.5 – 2.2)	1.9	(1.7 – 2.1)

Predicted DCS Risks and Pearson Residuals of Data Sets in Reference 8

Data Set	N	Observed	Predictions								
			JAP98			ASYM - H/R			ASYM - H		
			Predictions Pearson Residual	Predictions Pearson Residual	Predictions Pearson Residual	Predictions Pearson Residual	Predictions Pearson Residual	Predictions Pearson Residual			
Single Air											
DC4D	797	19.4	15.3	1.120	19.0	0.009	19.9	0.013			
EDU557	568	27	35.8	2.309	26.4	0.014	27.5	0.009			
EDU885A	483	30	26.5	0.489	22.9	2.311	23.4	1.956			
UPS290	299	4	3.7	0.025	3.8	0.011	4.5	0.056			
DC4W	244	8.4	7.0	0.288	6.4	0.642	6.8	0.387			
EDU1351NL	143	2.7	3.4	0.148	3.7	0.277	3.9	0.379			
EDU849LT2	141	29.8	7.4	71.561	5.9	101.043	6.3	91.758			
NMR97NOD	103	3.4	6.0	1.196	4.7	0.376	4.7	0.377			
EDU545	94	18.7	7.4	18.730	5.0	39.647	5.1	38.347			
NMRNSW2	91	5.5	6.8	0.269	5.2	0.018	5.2	0.018			
PASA	72	5.2	3.6	0.748	3.1	1.486	3.1	1.487			
SUBX87	58	2	0.6	3.301	0.4	6.444	0.4	6.444			
EDU1157	46	15.6	13.4	0.510	11.5	1.949	17.8	0.443			
Single Non Air											
NMR8697	477	12.8	16.4	0.818	17.1	1.212	16.4	0.818			
EDU1180S	120	10	10.1	0.001	6.1	2.627	6.4	2.139			
EDU885M	81	4	4.77	0.132	3.4	0.110	3.5	0.075			
Repetitive and Multilevel Air											
PAMLA	236	14.2	21.0	2.417	16.2	0.265	17.0	0.497			
EDU885AR	182	11	14.4	0.872	11.3	0.008	11.6	0.033			
DC4DR	142	1	6.7	5.089	6.9	5.302	6.7	5.089			
EDU657	142	4	10.3	4.155	8.4	2.450	8.6	2.619			
PARA	135	7.3	11.6	1.744	10.4	1.001	10.4	1.001			
DC4WR	12	3	1.2	3.000	0.8	6.482	0.8	6.482			
Repetitive and Multilevel Non-Air											
EDU184	239	11	18.2	3.083	16.2	1.790	16.9	2.216			
PAMLOAS	140	5.3	7.0	0.434	6.7	0.307	6.4	0.198			
PAMLAOD	134	6	8.3	0.679	7.4	0.280	7.4	0.280			
EDU1180R	128	2	14.2	11.789	10.7	7.719	12.5	9.774			
EDU885S	94	4	5.5	0.434	4.6	0.082	4.6	0.082			

Appendix B

Predicted DCS Risks of the Present U.S. Navy Decompression Tables

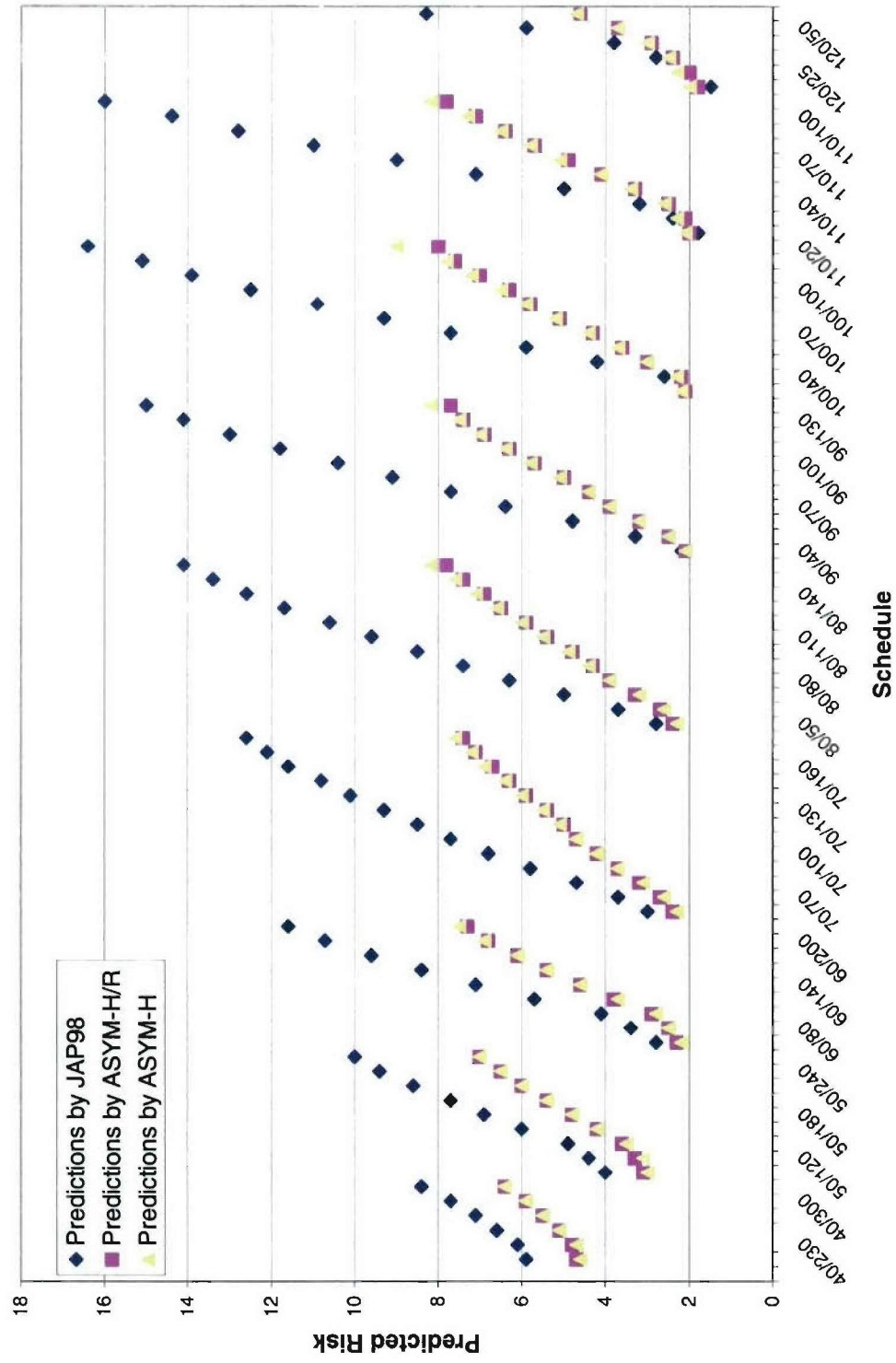
a) Air Tables

b) Sur-D O₂ Tables

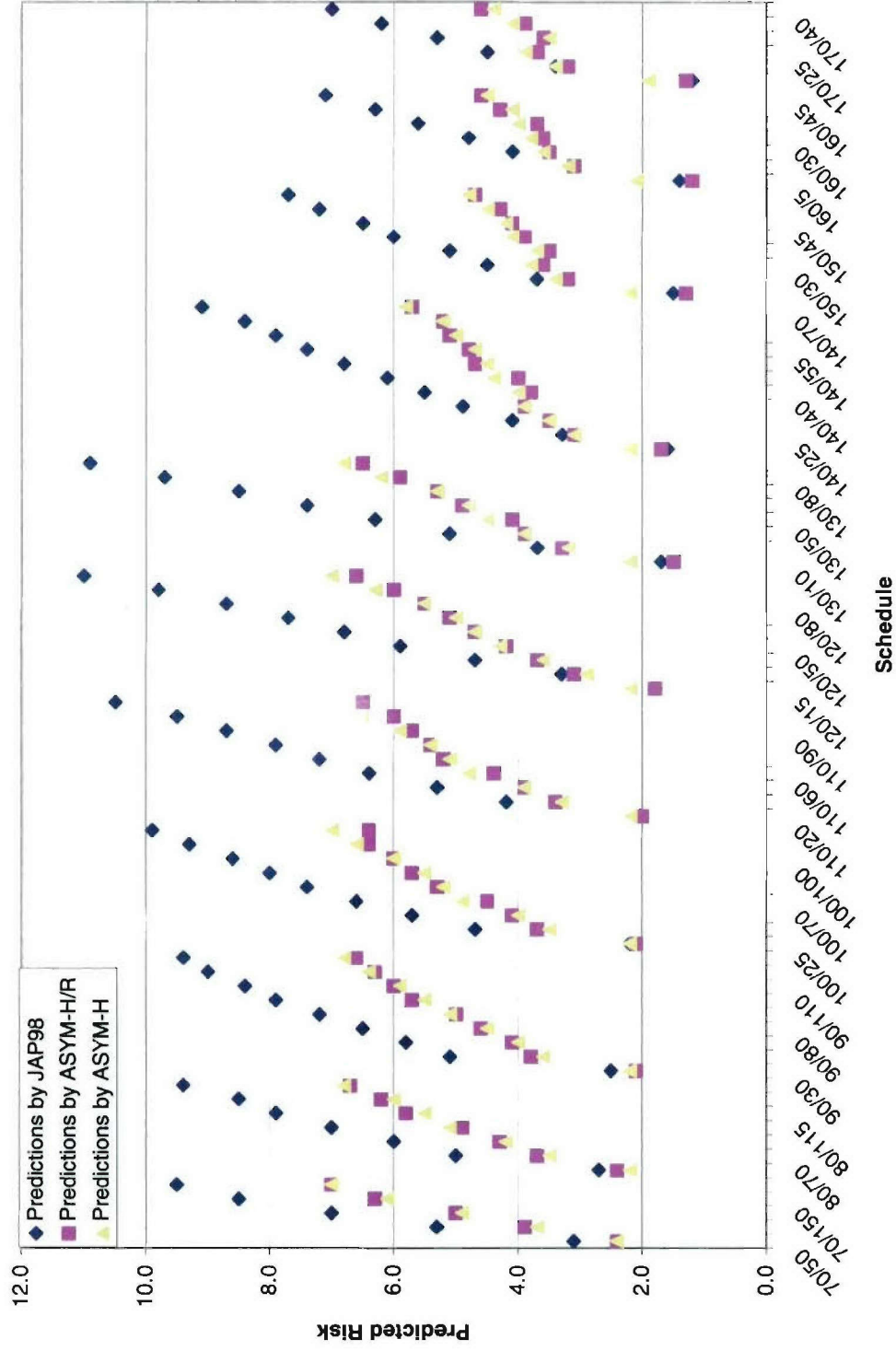
Using the JAP98, ASYM Human/Rat, (ASYM-H/R) & ASYM
Human-only (ASYM-H) Models

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Predicted DCS Risks of USN Air Decompression Tables



Predicted DCS Risks of USN Surface Decompression Tables



Appendix C

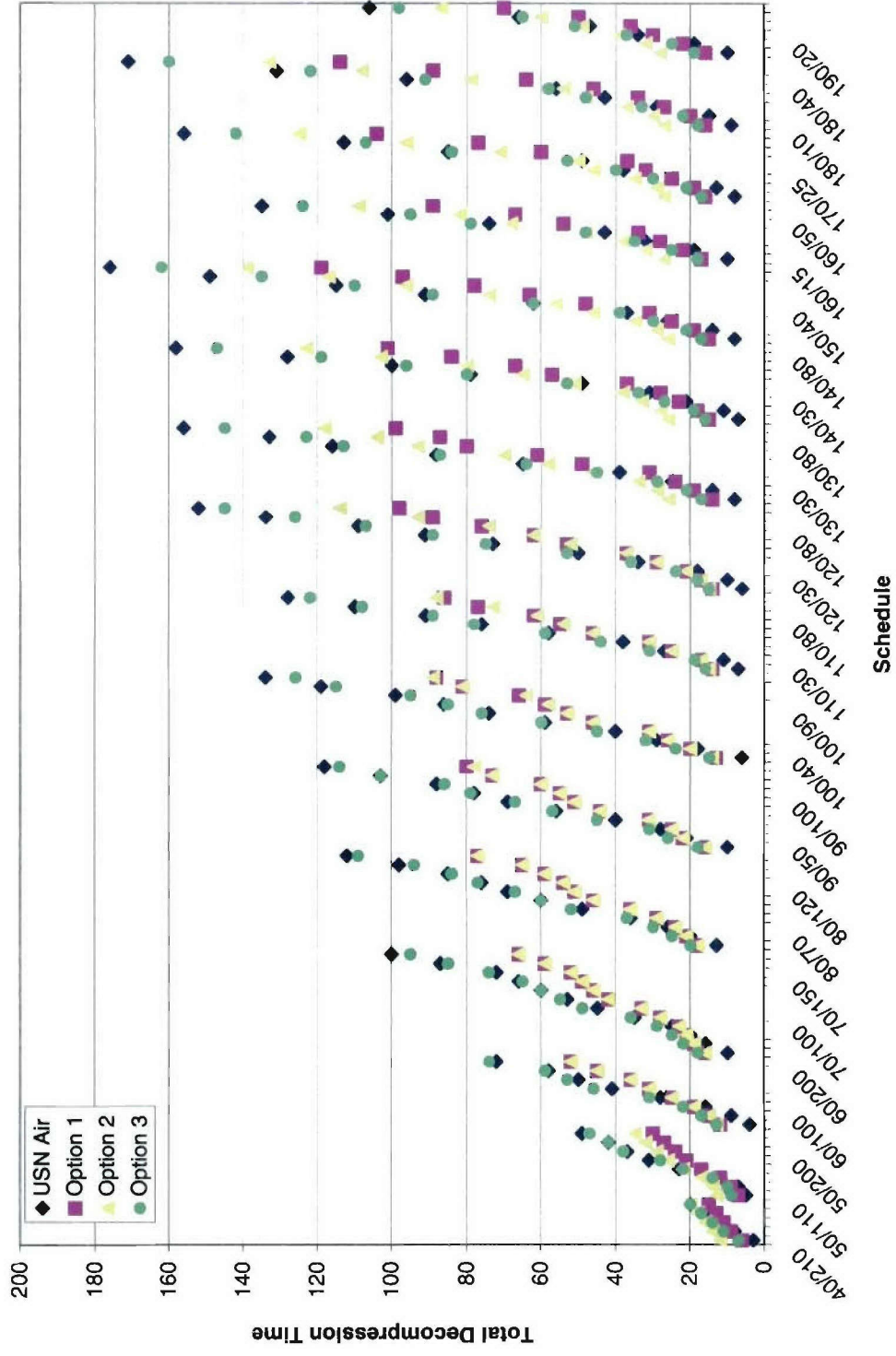
Comparison of Decompression Times of Proposed Options

a) with present Air Tables (USN Air)

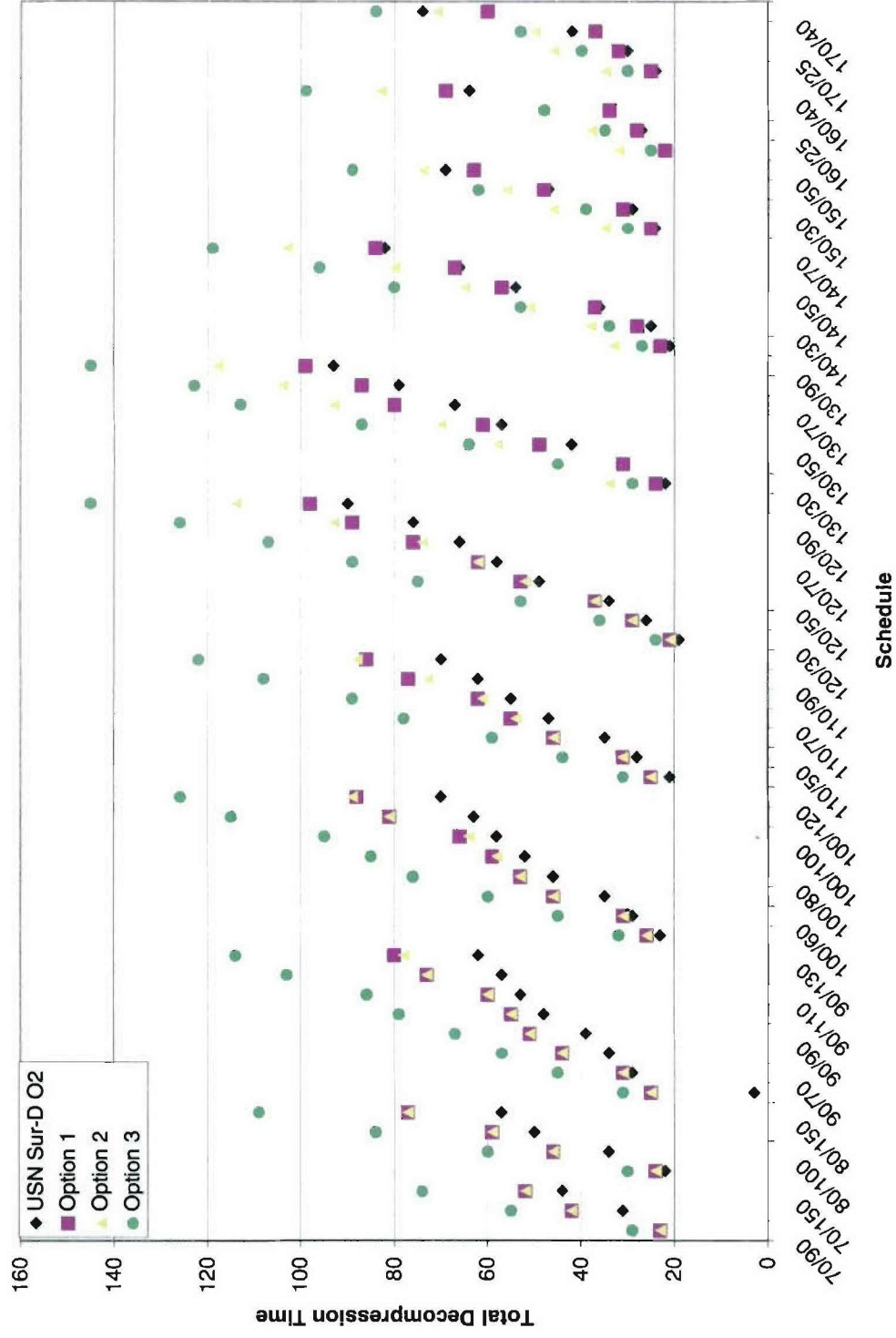
b) with present Sur-D O₂ Tables (USN Sur-D O₂)

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Comparison of Decompression Time



Comparison of Decompression Time



Appendix D

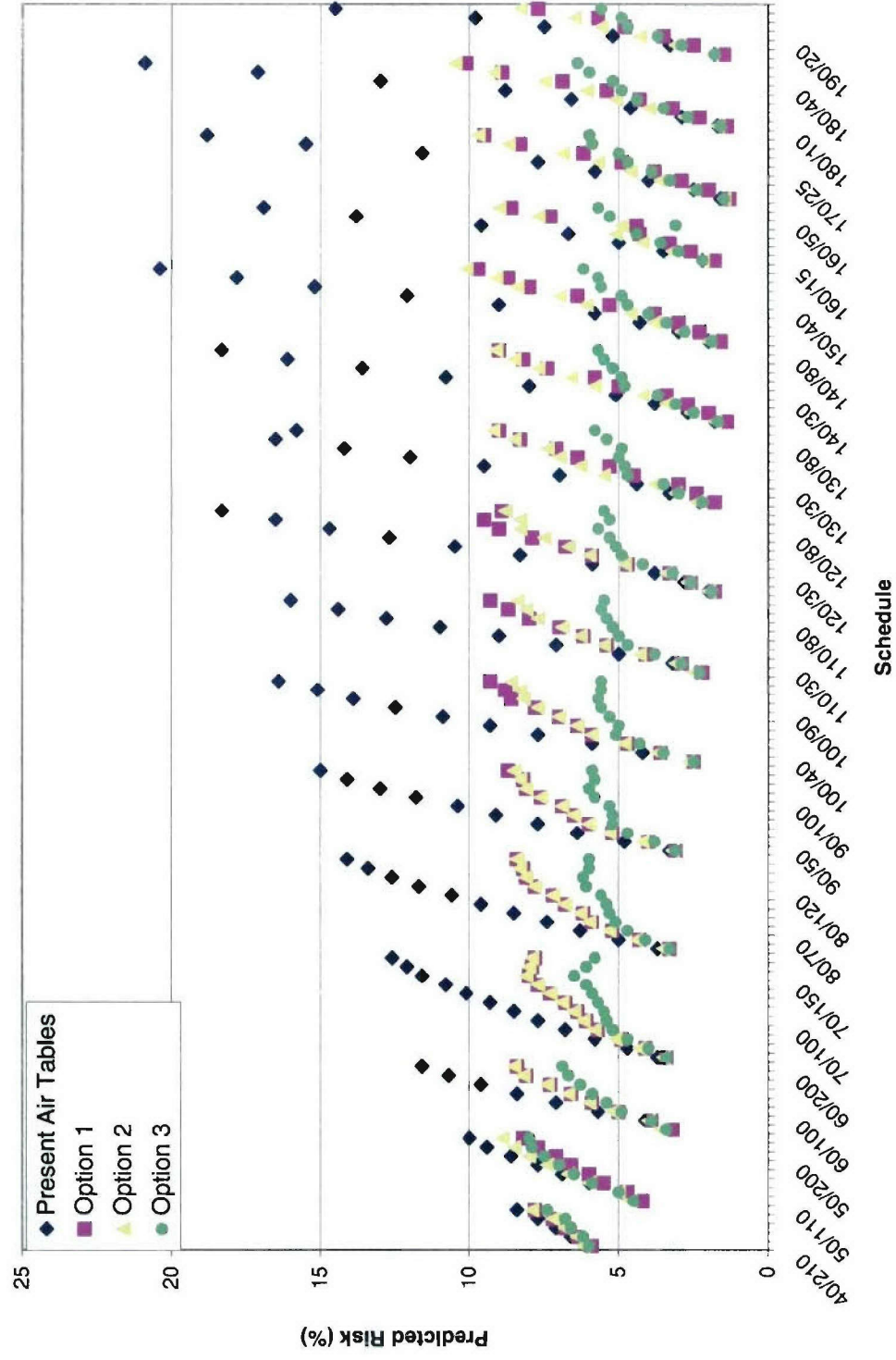
Risk Comparison of Proposed Options with Present Air Tables

Using the JAP98, ASYM Human/Rat, (ASYM-H/R) & ASYM

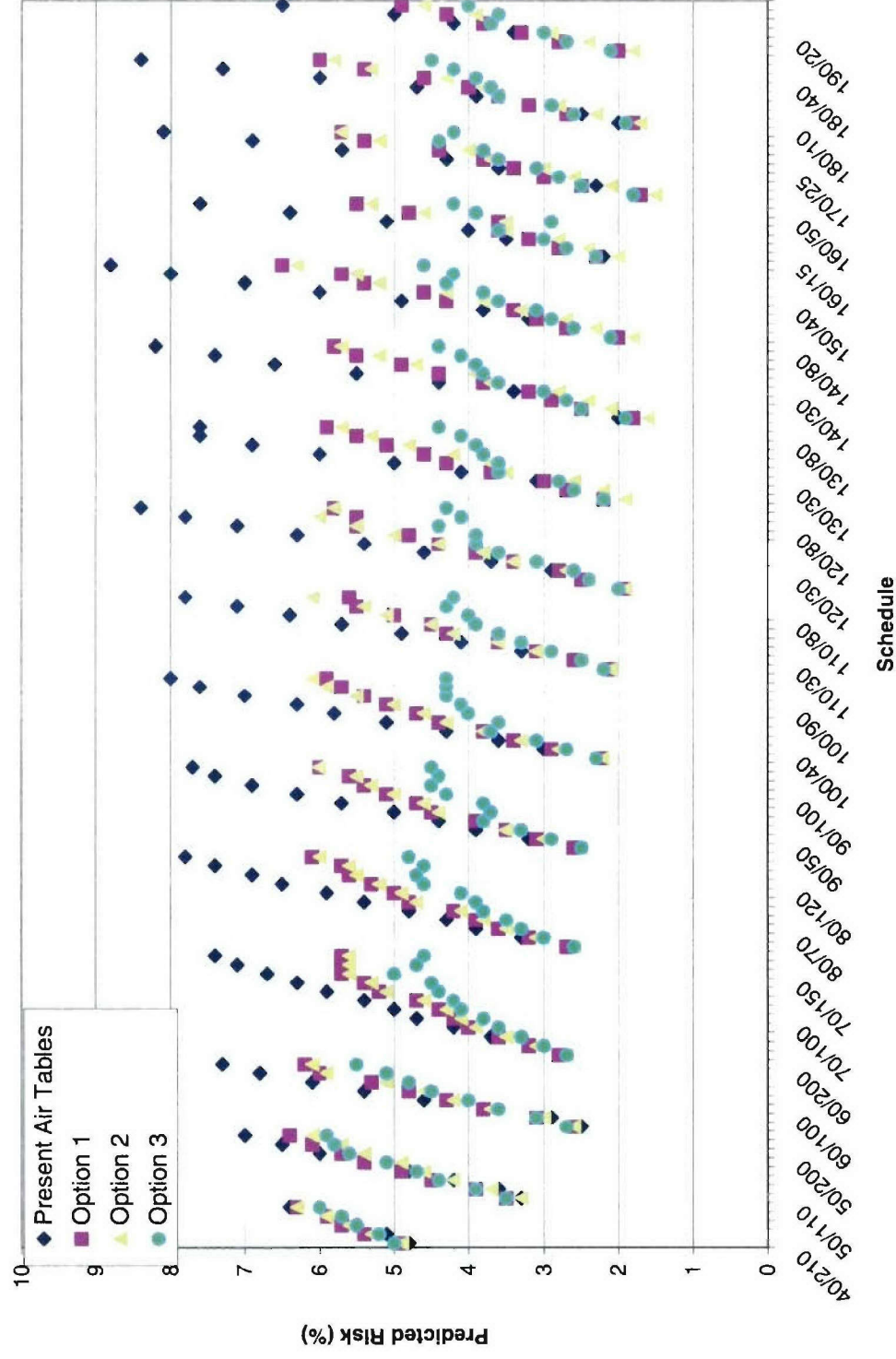
Human-only (ASYM-H) Models

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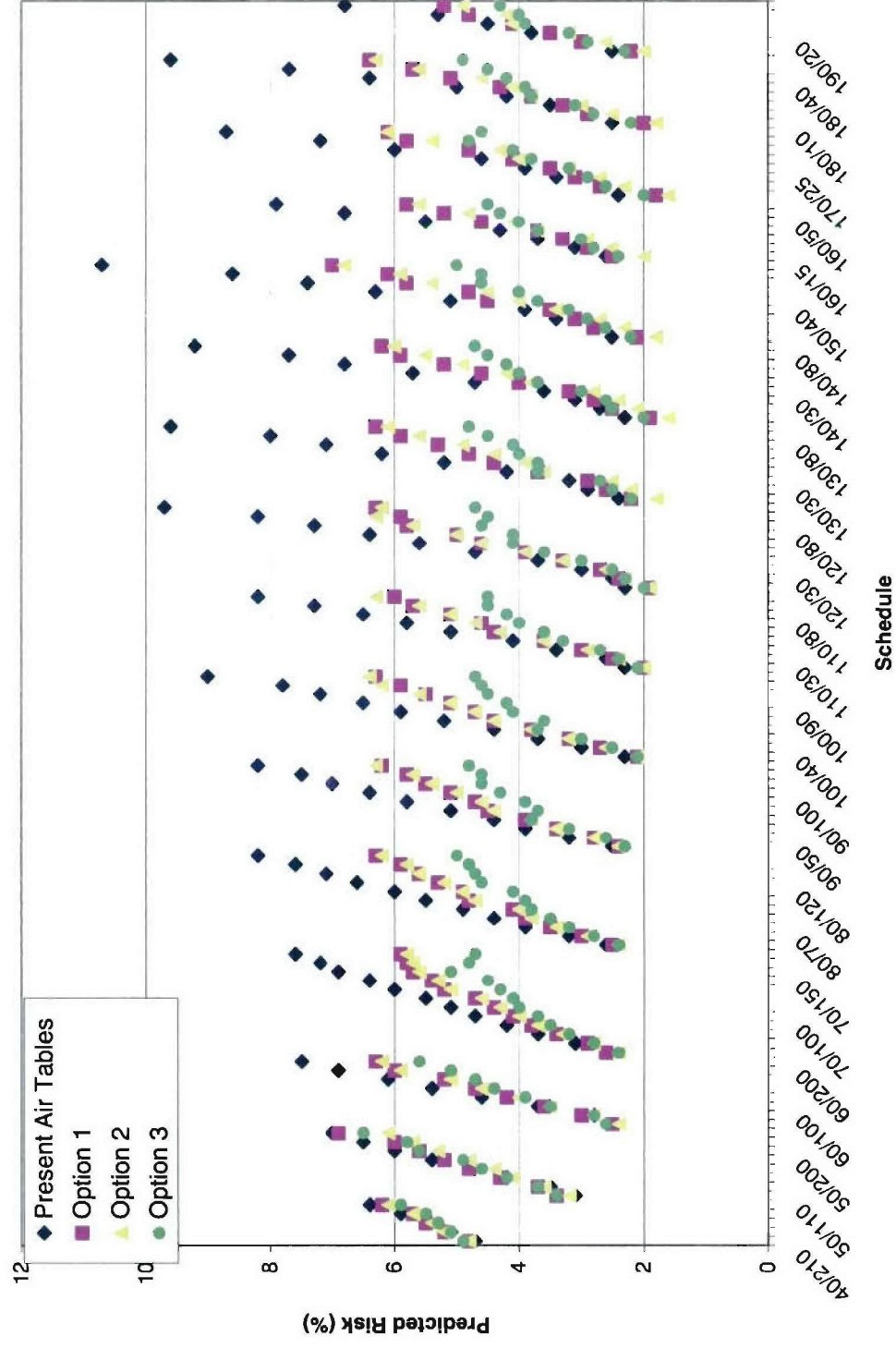
Risk Comparison of Proposed Sur-D O2 Options Using JAP98



Risk Comparison of Proposed Sur-D O2 Options Using ASYM-H/R



Risk Comparison of Proposed Sur-D O2 Options Using ASYM-H



Appendix E

Risk Comparison of Proposed Options

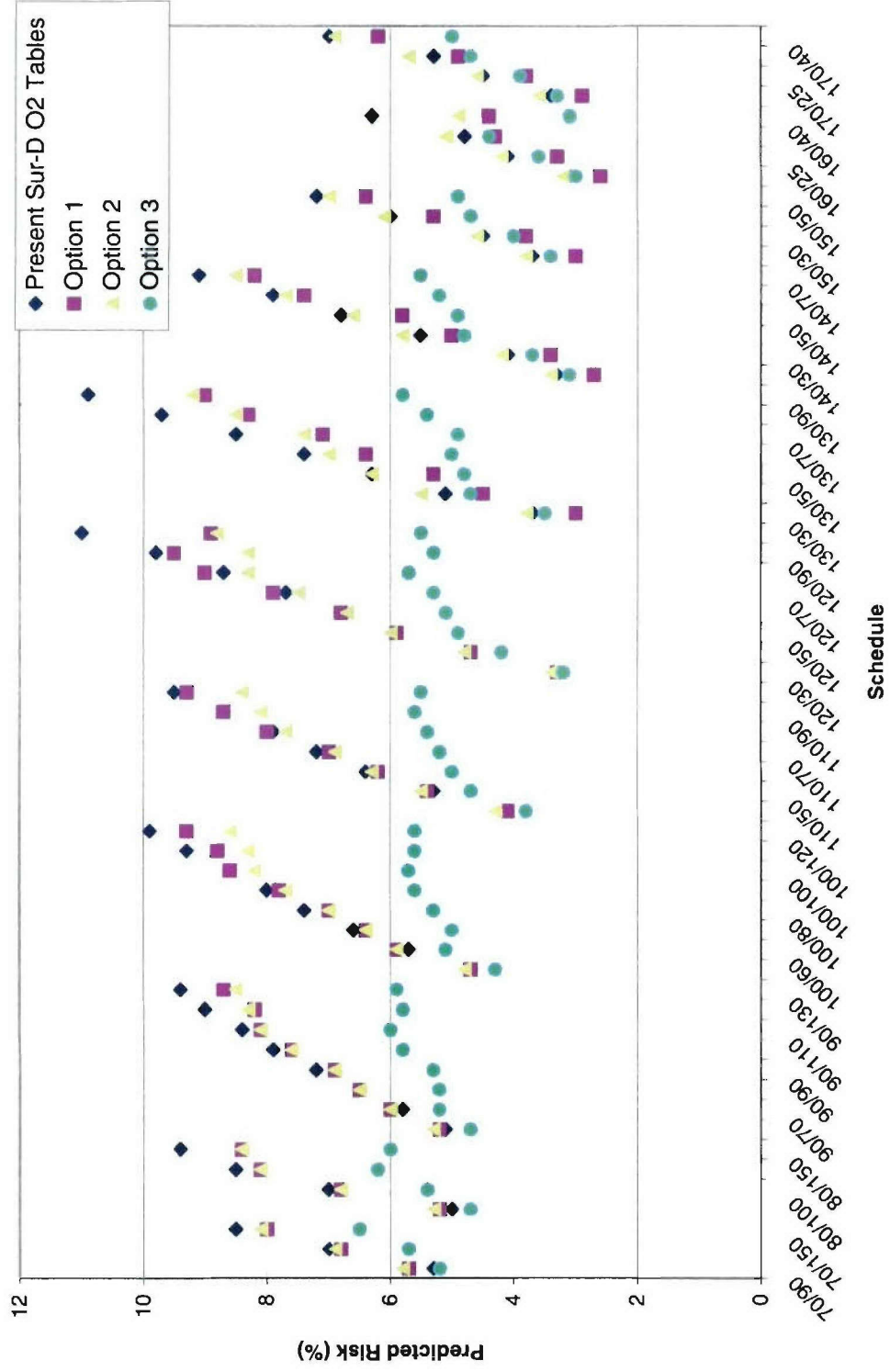
with Present Sur-D O₂ Tables

Using the JAP98, ASYM Human/Rat, (ASYM-H/R) & ASYM

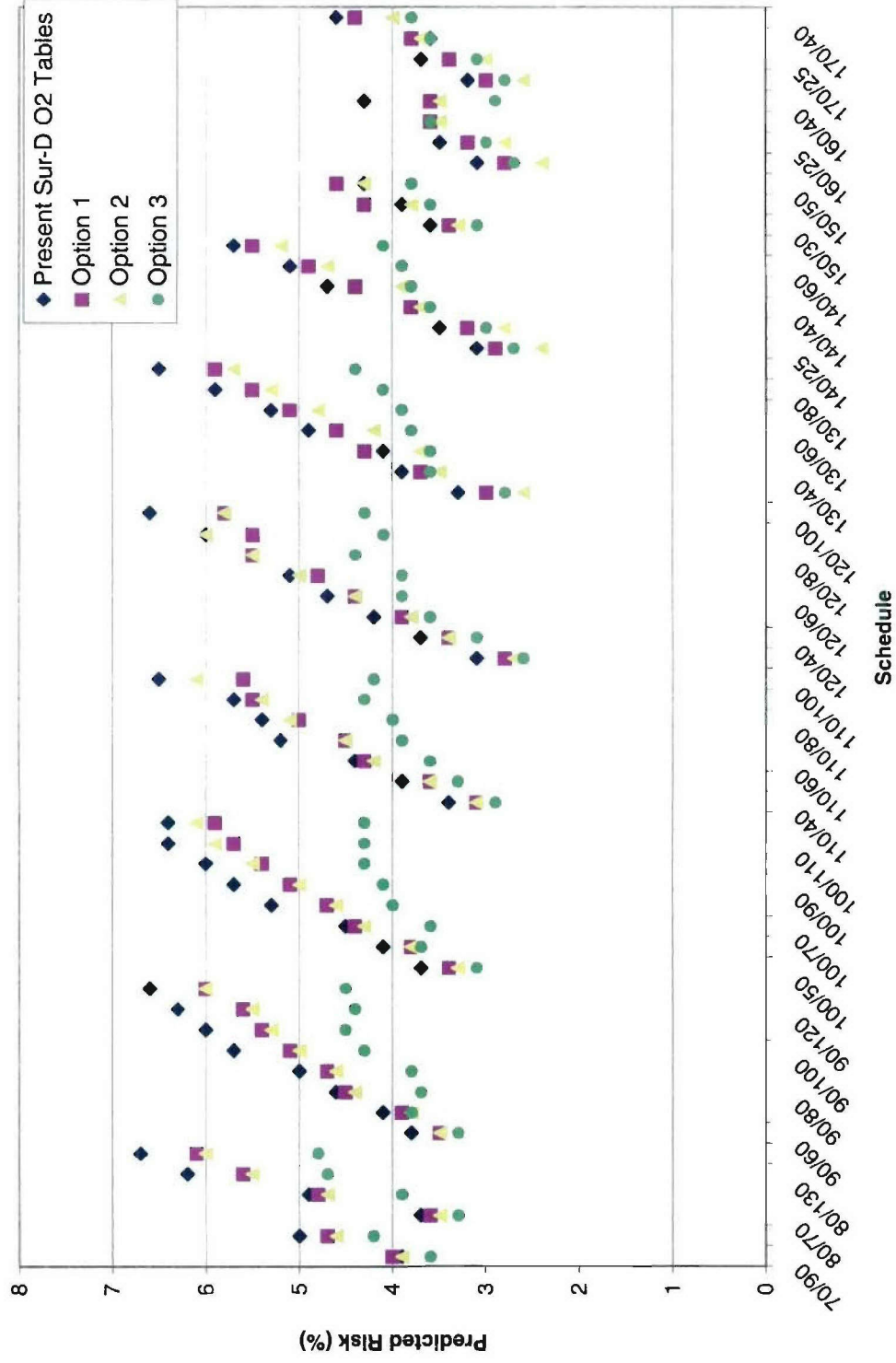
Human-only (ASYM-H) Models

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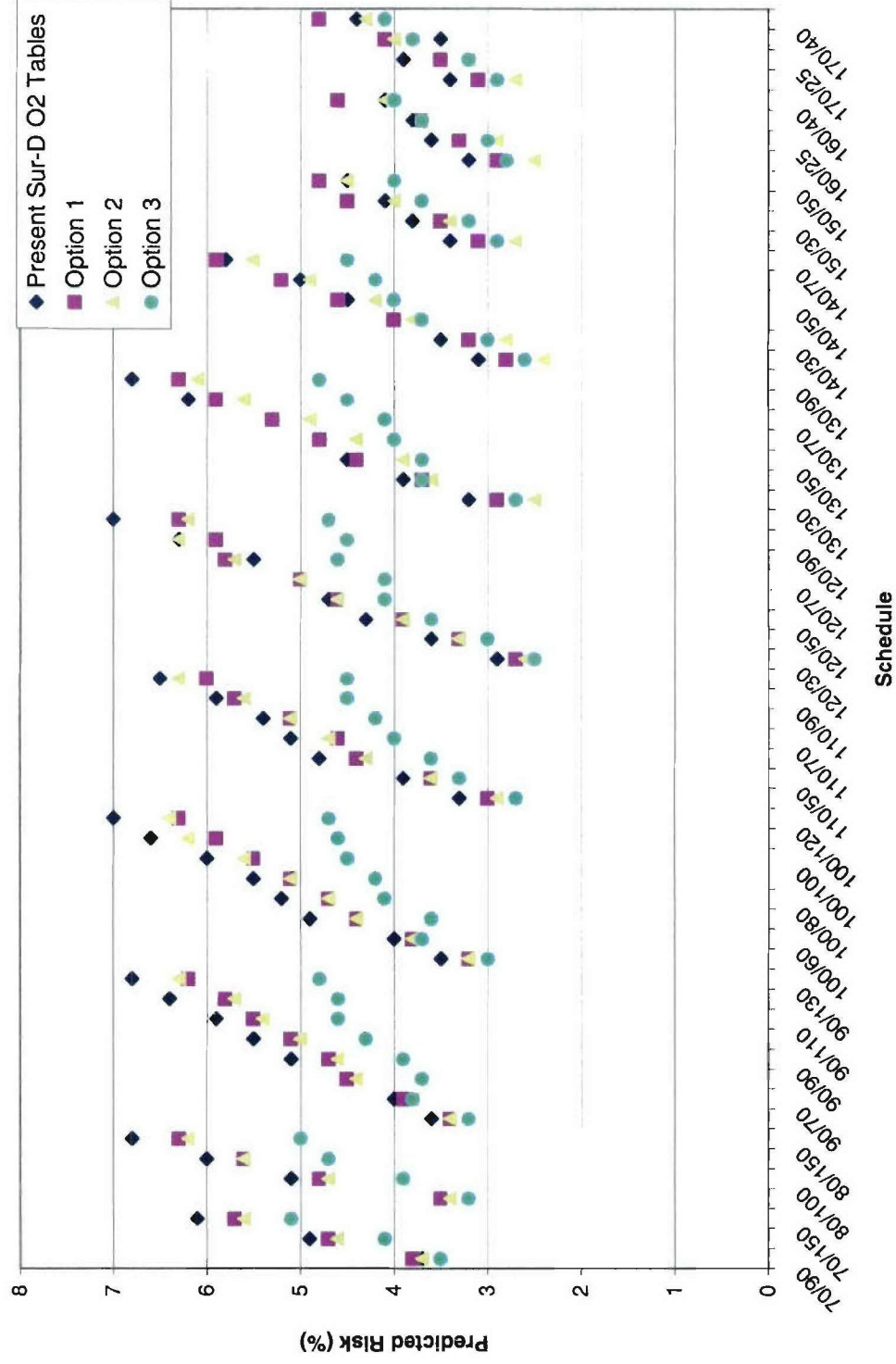
Risk Comparison of Proposed Sur-D O2 Options Using JAP98



Risk Comparison of Proposed Sur-D O2 Options Using ASYM-H/R



Risk Comparison of Proposed Sur-D O2 Options Using ASYM-H



Appendix F

Standard Profiles with 95% Confidence Intervals for the Predictions of the Three Models

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Standard Profiles with Confidence Intervals for the Predictions of the Three Models.

Profile Description (All air dives, unless noted)	Risk Predicted by Model (%)		
	JAP98	ASYM Human/Rat	ASYM Human-only
Submarine escape from 400 fsw in SEIE	2.7 – 7.1	4.5 – 11.8	4.3 – 12.7
Submarine escape from 600 fsw in SEIE (2.7 min)	6.9 – 13.1	7.6 – 18.3	7.2 – 20.8
60 fsw for 60 min ascent 60 fsw/min	1.5 – 2.9	2.1 – 2.9	1.9 – 2.7
60 fsw for 60 min ascent 20 fsw/min	1.4 – 2.8	1.7 – 2.6	1.6 – 2.5
60 fsw for 80 min ascent 60 fsw/min	2.5 – 4.1	2.9 – 4.0	2.8 – 3.7
60 fsw for 80 min ascent 20 fsw/min	2.4 – 4.0	2.6 – 3.6	2.6 – 3.6
49 fsw for 60 min on 10% Oxygen (60/60 equiv)	1.6 – 3.0	1.9 – 2.9	1.8 – 2.6
80 fsw for 60 min on 35% Oxygen (60/60 equiv)	1.0 – 3.3	2.2 – 3.4	2.1 – 3.0
20 fsw saturation ascent 60 fsw/min	5.4 – 8.2	4.4 – 7.3	4.2 – 5.9
25 fsw saturation ascent 60 fsw/min	8.7 – 13.0	9.0 – 15.5	5.5 – 12.8
30 fsw saturation ascent 60 fsw/min	12.0 – 18.2	16.3 – 27.0	12.4 – 25.1
60 fsw for 180 min by USN in-water schedule	7.4 – 11.1	5.9 – 7.9	5.9 – 8.0
60 fsw for 180 min by USN93 schedule	5.0 – 7.7	4.9 – 6.6	5.0 – 6.8
60 fsw for 180 min with 14 min O ₂ at 20 fsw	6.5 – 9.6	5.5 – 7.7	5.7 – 7.6
60 fsw for 180 min with 14 min O ₂ during ascent	6.4 – 9.6	5.4 – 7.5	5.7 – 7.6
60 fsw for 180 min by USN Sur-D O ₂ schedule — 1 min SI	4.2 – 7.1	4.6 – 6.3	4.6 – 6.1
60 fsw for 180 min by USN Sur-D O ₂ schedule — 3.5 min SI	4.3 – 7.1	4.6 – 6.4	4.7 – 6.4
60 fsw for 180 min by USN Sur-D O ₂ schedule — 6 min SI	4.3 – 7.1	4.6 – 6.4	4.7 – 6.5
60 fsw for 180 min — 1 hour Oxygen at 20ft	1.1 – 3.9	3.2 – 5.3	3.6 – 4.7
TWA 800 — 116/85 on the 120 for 90 Sur-D O ₂ schedule	5.2 – 8.1	4.3 – 6.2	4.6 – 6.3
TWA 800 — 116/59 on the 120 for 90 Sur-D O ₂ schedule	2.1 – 4.2	2.5 – 4.0	2.6 – 3.8

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